Searching for the Scalar of the Strongly-Coupled Standard Model

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Abstract

We investigate decays of the scalar bound state present in the Abbott-Farhi model. We show that decays with photons in the final state may have large branching ratios. We also show that operators coupling the scalar particle to two photons or to a photon and a Z^0 are not seriously constrained by electroweak data, unlike other sectors of the Abbott-Farhi model.

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1   Introduction

Precise measurements of electroweak parameters [1] have ruled out or severely constrained many models. Although measurements with such a high level of precision give some insight into high-energy phenomena, there still exists a low-energy alternative to the Standard Model (SM) of electroweak interactions, namely the Abbott-Farhi model [2]. The Abbott-Farhi model, or the Strongly-Coupled Standard Model (SCSM), has the same Lagrangian as the Minimal SM, however the $SU(2)_L$ coupling constant becomes large at a characteristic scale higher than the electroweak symmetry breaking scale in the SM. $SU(2)_L$ interactions are confining below that scale. Parameters of the scalar sector are adjusted so that the $SU(2)_L$ symmetry is not broken. Below the confinement scale the particles are composite objects. The spectrum of the lightest particles consists of fermions, the photon, three massive spin-one bosons and one spinless particle.

Fermions are bound states of a fundamental fermion and a scalar. Spin-one particles are bound states of two fundamental scalars; their interactions resemble the interactions of the massive gauge bosons of the SM. The composite scalar is a bound state of two fundamental scalars, and its experimental signatures may be similar to those of the Higgs particle of the Minimal SM. The composite particles do not carry any net $SU(2)_L$ charge, just as the physical, hadronic states of QCD carry no net color.

At low energies, the interactions of the composite particles can be described in terms of an effective Lagrangian. Neglecting higher-dimensional operators and heavier, yet unobserved, particles, the low-energy couplings of vector bosons to fermions are identical to those of the SM. Thus, the low-energy effective theory of such particles, under certain assumptions, reproduces physics of the SM [2, 3]. Deviations from SM predictions test the magnitude of higher-dimensional operators and the presence of exotic particles predicted by the SCSM: excited fermions, excited vector bosons, as well as diquarks, dileptons and leptoquarks. For a more detailed description of the model see Ref. [3]. However, there are some arguments based on lattice studies and continuum field theory [4, 5] that the confining phase of the $SU(2)_L$ theory breaks chiral symmetries, and consequently there cannot be light fermions present in the particle spectrum. It is not entirely clear if those arguments apply to the Abbott-Farhi model, since Yukawa couplings, strong $SU(3)$ and hypercharge $U(1)$ gauge interactions were not taken into account.

Experiments before LEP did not seriously constrain the exotic sector of the SCSM [6]. A recent analysis of the model [7] shows that the SCSM is now so constrained that it may look unnatural. However, the SCSM cannot be ruled out, as the exotic sector of the model does not influence low-energy measurements (up to the Z^0 mass) in the limit of heavy exotic particles and weak couplings. Another way to confirm or rule out the SCSM could be the observation of new particles. It is possible that, for some reason, the excited vector

bosons analyzed in [7] are very heavy or else weakly coupled. Then the first new particle to be observed could be the the lightest scalar particle. Can we distinguish the SCSM scalar from the SM Higgs boson? If the SCSM is the true theory of the weak interactions, at the phenomenological level, fermions and vector particles are very similar to their SM counterparts. It might well be that the total width of the SCSM scalar and its partial widths of decays to fermions and massive vector bosons are experimentally indistinguishable from those predicted for the SM Higgs boson. However, the composite nature of the scalar particle may show up in some decay channels of such a particle, especially decays with photons in final state.

In this letter we analyze decays of the scalar particle into two photons or into a photon and a Z^0. In the SM, couplings of the Higgs particle to two photons or one photon and the Z^0 are absent at the tree level, since the Higgs particle is a fundamental neutral field. Such couplings first appear at the one-loop level. In the SCSM, the photon can interact directly with the charged constituents of the scalar bound state, making couplings considerably larger than the one-loop level couplings in the SM. Large branching ratios of the decays $\phi \to \gamma\gamma$ and $\phi \to \gamma Z^0$ can be a clear signal for physics beyond the Minimal SM, and in particular, a signal for the SCSM. We argue that operators responsible for decays of the scalar into final states including photons may have very large magnitudes in the SCSM. We estimate the numbers of such events that would be observable at the LHC. Finally, we show that those operators are indeed not significantly bounded by present electroweak data.

2   The decays $\phi \to \gamma\gamma$ and $\phi \to \gamma Z^0$

The physical scalar particle of the SCSM is a bound state of fundamental charged scalar fields, $\phi = \varphi_\alpha^* \varphi^\alpha$, where φ^α is a fundamental scalar field, and α is an $SU(2)_L$ index. Fermion masses and fermion-scalar couplings for the composite field both arise from Yukawa couplings of the elementary Higgs in the underlying Lagrangian. Thus, the Yukawa couplings in the effective theory are proportional to the fermion masses. The remaining couplings of the scalar particle cannot be deduced without solving the confining dynamics of the model. We therefore investigate two dimension-five operators that could be large in the SCSM:

$$O_{\gamma\gamma} = \frac{a}{\Lambda} \phi F_{\mu\nu} F^{\mu\nu} \text{ and } O_{\gamma Z} = \frac{b}{\Lambda} \phi F_{\mu\nu} Z^{\mu\nu}, \tag{1}$$

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$, $Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu$ (no commutator), and Λ is the characteristic scale of $SU(2)_L$ interaction. These operators are the lowest-dimensional operators consistent with electromagnetic gauge invariance that give rise to the decays $\phi \to \gamma\gamma$ and $\phi \to \gamma Z^0$. Composite particles of the SCSM are $SU(2)_L$ singlets, thus any operator written in terms

of composite fields is already $SU(2)_L$ invariant. By contrast, in the SM, an operator like $hF_{\mu\nu}Z^{\mu\nu}$ included in the Lagrangian would spoil the gauge invariance.

Let us consider the operator $O_{\gamma\gamma}$ and estimate its coefficient using conventional dimensional analysis [8]. Operators are constructed from dimensionless combinations like $eF_{\mu\nu}/\Lambda^2$ and ϕ/v, and multiplied by $v^2\Lambda^2$, where e is the unit charge, v is the electroweak symmetry breaking scale ≈ 250 GeV, and Λ is of the order $4\pi v$. This estimate gives $O_{\gamma\gamma} = [e^2/(4\pi\Lambda)]\phi F_{\mu\nu}F^{\mu\nu}$. $\Lambda \approx 4\pi v$ is the scale of physics beyond the SM. In the SCSM, Λ can be identified with the scale of $SU(2)_L$ interactions. Hence, the coefficient a in Eq. (1) is equal to $\frac{e^2}{4\pi}$. However, this estimate may be completely irrelevant in case of the SCSM. Dimensional analysis is based on the assumption that the derivative expansion of an effective Lagrangian works as naively expected, i.e. higher-dimensional terms are small, comparable to loop corrections of operators with fewer derivatives. The SCSM requires an additional assumption [3] in order to reproduce the observed weak interactions: the vector bosons W and Z have to be unnaturally light, much lighter than the scale of $SU(2)_L$ interactions. This assumption should be contrasted with knowledge from QCD, where all particles (except Goldstone bosons) are heavier than the scale Λ_{QCD}.

It may indicate that the dynamics of the SCSM are quite complicated, and consequently the derivative expansion of the Lagrangian may be unconventional. This allows the possibility that in the SCSM the operators $O_{\gamma\gamma}$ and $O_{\gamma Z}$ could have much bigger magnitude than naively expected. The operator $O_{\gamma\gamma}$ can arise from the diagram illustrated in Fig. 1. Photon fields couple directly to charged scalar preons. The diagram shown in Fig. 1 is not a loop diagram in the sense of perturbation theory because the couplings of the $SU(2)_L$ bosons are non perturbative. The magnitude of the operator $O_{\gamma\gamma}$ is proportional to the magnitude of preon wave function at the origin. We assume that in the SCSM the magnitudes of the operators $O_{\gamma\gamma}$ and $O_{\gamma Z}$ are not suppressed by non-perturbative effects, so the magnitudes can be as large as $a = e^2$ and $b = e$. We will show in the next chapter that such large coefficients are allowed by current experimental data.

Operators $O_{\gamma\gamma}$ and $O_{\gamma Z}$ induce decays of the scalar particle: $\phi \to \gamma\gamma$ and $\phi \to \gamma Z^0$. The resulting partial widths are then:

$$\Gamma(\phi \to \gamma\gamma) = \frac{|a|^2}{\Lambda^2}\frac{m_\phi^3}{2\pi}, \tag{2}$$

$$\Gamma(\phi \to \gamma Z) = \frac{|b|^2}{\Lambda^2}\frac{m_\phi^3}{8\pi}(1 - \frac{m_Z^2}{m_\phi^2})^3, \tag{3}$$

where m_ϕ is the mass of the scalar particle. As we mentioned before, the magnitude of coupling between the scalar and a pair of fermions is proportional to the fermion mass. Also the couplings of the scalar to the W and Z bosons can have magnitudes close to those of the SM Higgs particle, since the couplings are described by dimension-three operators, which

3

are not suppressed by a large mass scale. However, the magnitudes of couplings between the scalar and two photons or a photon and a Z^0 can be much larger than in the SM. Thus the $\phi \rightarrow \gamma\gamma$ and $\phi \rightarrow \gamma Z^0$ decay modes are particularly interesting to search for. By looking for these decays the SCSM scalar can be discovered and, perhaps, distinguished from the SM Higgs boson.

In Fig. 2 we present the widths of the decays $\phi \rightarrow \gamma\gamma$ and $\phi \rightarrow \gamma Z^0$ computed from Eqs. (2) and (3), with $a = e^2$ and $b = e$. The widths are normalized to the total width of the Higgs boson in the Minimal SM [9]. We cannot rigorously compute the total width of the scalar in the SCSM. The normalization serves only as a reference point. Clearly, branching fractions are much larger in the SCSM than in the SM, where they are of the order 10^{-4} [9].

In Table 1 we present an estimate of the number of events for both decay channels expected at the LHC in one year of running with an integrated luminosity of 10^5 pb^{-1} [10]. We have again assumed that the production cross section for the SCSM scalar is the same as for the Minimal SM Higgs boson.

The widths of the dominant decay channels of the SCSM scalar are likely to be similar to those of the SM Higgs particle. If the scalar is lighter than about 150 GeV, decays into $b\bar{b}$ and $\tau^+\tau^-$ pairs will dominate. In this mass range the scalar particle has a very small width, and can have BR($\phi \rightarrow \gamma\gamma$) as big as 10%. The $\phi \rightarrow \gamma\gamma$ channel is a clean and easy discovery mode of the SCSM scalar particle. The number of events is so large that even if the mass of the scalar coincides with the Z^0 mass, detection will be possible. Thus the $\phi \rightarrow \gamma\gamma$ decay mode is very interesting to look for both at the LEP-II and the LHC. The $\phi \rightarrow \gamma Z^0$ channel is interesting only in a very narrow mass range from approximately 120 to 150 GeV, where the branching ratio can reach a few percent.

If the scalar mass is above 150 GeV, the dominant decay mode will be to WW and ZZ pairs (one of the bosons may be off the mass shell). The partial width for the decays into a pair of vector bosons increases as the cube of the scalar mass. With the heavy top quark [11], decays into $t\bar{t}$ pairs will have quite a small branching ratio, and probably cannot be observed at the LHC. The most suitable channel for the detection of the SCSM scalar is likely to be the mode $\phi \rightarrow ZZ \rightarrow 4l$. However, the $\phi \rightarrow \gamma\gamma$ channel could give a signal with larger statistical significance, depending on the ability of the detector to suppress $\gamma\gamma$ background. For a $\gamma\gamma$ invariant mass of more then 200 GeV there is very little 'irreducible' background from $q\bar{q}, gg \rightarrow \gamma\gamma$ production. The main sources of background are misidentified π^0's and jets. Background rejection becomes a crucial feature of the detector for detection of a scalar heavier than 300 GeV. The width of the scalar is large, so background rejection may be more important than energy resolution. The expected number of events from background at the proposed CMS experiment corresponds to cross section 10 fb per 1-GeV bin of $\gamma\gamma$ invariant mass [12]. It will then be possible to observe the $\phi \rightarrow \gamma\gamma$ signal with a statistical significance greater than 5 for a scalar lighter than approximately 450 GeV.

The above discussion is based on the optimistic assumption that the magnitudes of the operators $O_{\gamma\gamma}$ and $O_{\gamma Z}$ are as large as they possibly can be. Should the actual magnitudes of these operators differ only slightly from their magnitudes in the SM, then information about the decays of the lightest scalar into two photons or a photon and a Z^0 are not enough to tell the SCSM from the SM or myriads of its extensions.

3   Oblique corrections

We are now going to show, as claimed earlier, that the operators $O_{\gamma\gamma}$ and $O_{\gamma Z}$ are not sufficiently restricted by current precise electroweak measurements to exclude their having large magnitudes. We use the formalism of oblique corrections. Operators $O_{\gamma\gamma}$ and $O_{\gamma Z}$ contribute to self-energies of the vector bosons, and they do not give any significant contribution to four-fermion operators. Thus low-energy effects of these operators can be conveniently expressed in terms of the parameters S, T and U [13]. Self-energy diagrams are of the form shown in Fig. 3. A one-loop calculation performed using dimensional regularization gives:

$$
\begin{aligned}
\Pi_{\gamma\gamma}^{\mu\nu} &= \frac{|a|^2}{\pi^2\Lambda^2}(q^2 g^{\mu\nu} - q^\mu q^\nu)\left[\frac{m_\phi^2}{2}\left(D(m_\phi^2) + \frac{3}{2}\right) + O(q^2)\right], \\
\Pi_{\gamma\gamma}^{\mu\nu} &= \frac{|b|^2}{4\pi^2\Lambda^2}(q^2 g^{\mu\nu} - q^\mu q^\nu)\left[\frac{m_\phi^2 + m_Z^2}{2}\left(D(m_\phi^2) + \frac{3}{2}\right) + O(q^2)\right], \qquad (4)\\
\Pi_{ZZ}^{\mu\nu} &= \frac{|b|^2}{4\pi^2\Lambda^2}(q^2 g^{\mu\nu} - q^\mu q^\nu)\left[\frac{m_\phi^2}{2}\left(D(m_\phi^2) + \frac{3}{2}\right) + O(q^2)\right],
\end{aligned}
$$

where $D(m^2) = \frac{1}{2\epsilon} - \gamma - \log(\frac{m^2}{4\pi\mu^2})$. We assume that the operators $O_{\gamma\gamma}$ and $O_{\gamma Z}$ are independent, i.e. there is no accidental cancellation between their effects. The S, T and U parameters are UV convergent if the self-energy counterterms are related in the following way [14]:

$$
\begin{aligned}
\delta\Pi_{WW} = \delta\Pi_W, \qquad & \delta\Pi_{ZZ} = c_W^2\delta\Pi_W + s_W^2\delta\Pi_B, \\
\delta\Pi_{\gamma Z} = c_W s_W(\delta\Pi_W - \delta\Pi_B), \qquad & \delta\Pi_{ZZ} = s_W^2\delta\Pi_W + c_W^2\delta\Pi_B,
\end{aligned}
$$

where δ indicates a divergent counterterm, and s_W and c_W are, respectively, sine and cosine of the Weinberg angle. In our case these relations do not hold. Computing S, T, U directly from Eqs. (4) would give a divergent result. However, physical results have to be finite, so divergent quantities have to be canceled by contributions from some higher-dimensional operators. Vector boson self energies due to scalar loops are potentially enhanced by $\log(\Lambda^2/m_\phi^2)$, where Λ provides a natural cut-off for the effective theory. Retaining only logarithmically-enhanced

parts we obtain the following contributions to S, T and U:

$$S = \frac{s_W^2 c_W^2}{2\pi^2\alpha} \frac{-4|a|^2 m_\phi^2 + |b|^2 m_Z^2}{\Lambda^2} \log(\frac{\Lambda^2}{m_\phi^2}),$$

$$T = 0, \tag{5}$$

$$U = -\frac{s_W^2}{2\pi^2\alpha} \frac{4|a|^2 m_\phi^2 + |b|^2(m_\phi^2 + s_W^2 m_Z^2)}{\Lambda^2} \log(\frac{\Lambda^2}{m_\phi^2}).$$

There are also threshold contributions originating from confining effects at the scale Λ, but we neglect them.

Current limits on the S and U parameters do not exclude large magnitudes for the operators $O_{\gamma\gamma}$ and $O_{\gamma Z}$. For instance, for a 400 GeV scalar particle, $\Lambda = 1\mathrm{TeV}$ and $a = e^2$, the contributions from $O_{\gamma\gamma}$ are only $S = -0.013$ and $U = -0.017$, while experimental bounds are $S = -0.48 \pm 0.40$ and $U = -0.12 \pm 0.69$ [15]. The photon always couples with strength e, so the values $a = e^2$ and $b = e$ are upper bounds for the magnitudes of the operators $O_{\gamma\gamma}$ and $O_{\gamma Z}$, correspondingly.

4   Conclusions

In this paper we have examined the decays $\phi \to \gamma\gamma$ and $\phi \to \gamma Z^0$ of the scalar particle present in the Abbott-Farhi model. Since confining theories are not completely understood, one can not conclusively argue for or against the SCSM based upon the analysis of deviations from the SM. Despite the precision of current measurements, large partial widths of the decays $\phi \to \gamma\gamma$ and $\phi \to \gamma Z^0$ are not excluded in the SCSM. The SCSM scalar particle can be discovered at LHC by looking for $\phi \to \gamma\gamma$ decays as long as the scalar is lighter than 450 GeV. The observation of the decays $\phi \to \gamma\gamma$ and $\phi \to \gamma Z^0$ with partial widths larger than predicted by the SM would indicate new, interesting physics.

Acknowledgments

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Figure Captions

Figure 1. Feynman diagram contributing to the decay $\phi \to \gamma\gamma$. The external lines represent photon fields, while the internal lines represent strongly interacting $SU(2)_L$ bosons.

Figure 2. Branching ratios of the $\phi \to \gamma\gamma$ and $\phi \to \gamma Z^0$ channels for $\Lambda = 1$ TeV.

Figure 3. Self-energy diagram. The blobs represent $O_{\gamma\gamma}$ or $O_{\gamma Z}$, and V is either γ or Z.

Table Caption

Table 1. The number of events for the decays $\phi \to \gamma\gamma$ and $\phi \to \gamma Z^0$ at the LHC computed for an integrated luminosity of 10^5 pb^{-1}.

Table 1

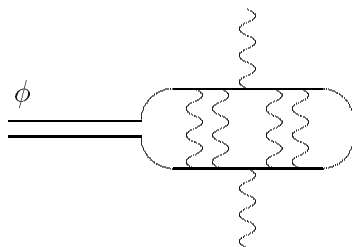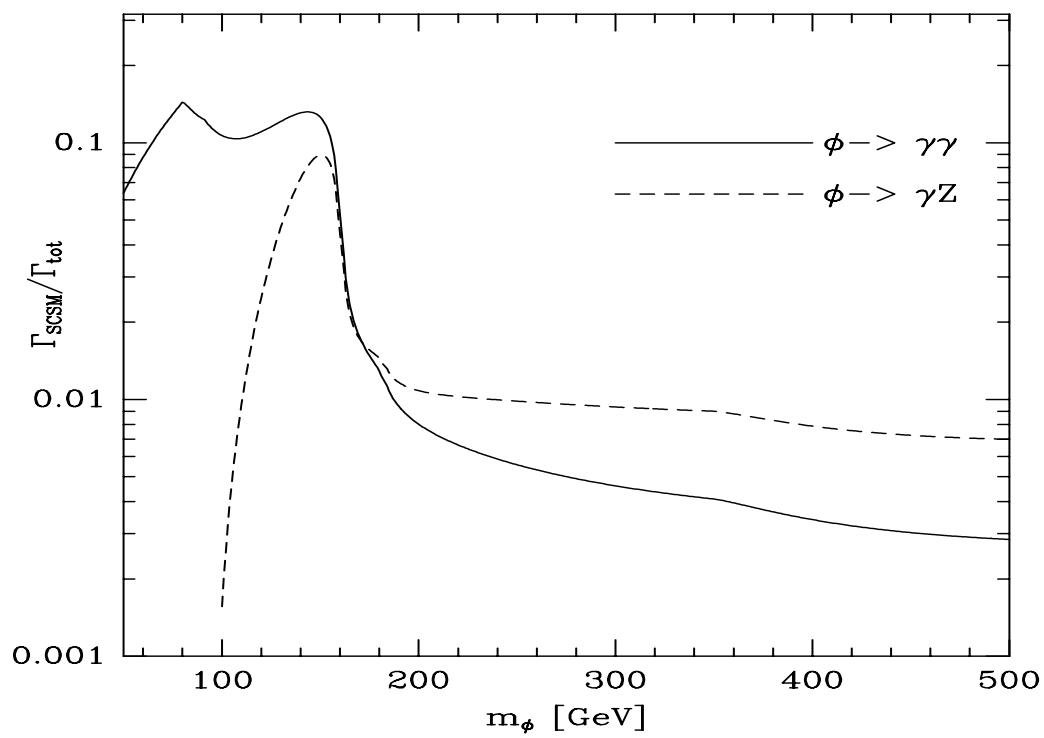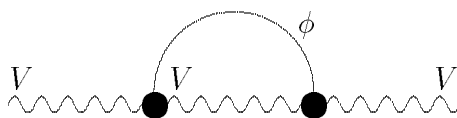| m_ϕ [GeV]	100	200	300	400	500
ϕ / year	5×10^6	4×10^6	10^6	4×10^5	2×10^5
$\phi \to \gamma\gamma$	5×10^5	3.6×10^4	5×10^3	1.2×10^3	600
$\phi \to \gamma Z^0$	5×10^3	4×10^4	10^4	3.2×10^3	1.4×10^3

Figure 1.

Figure 2.

Figure 3.